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EXPERIMENTAL DETERMINATION OF TEXTURE AND MECHANICAL ANISOTROPY OF TENSILE PROPERTIES IN COMMERCIALLY PURE TITANIUM SHEET

TECHNICAL REPORT

by

ANTHONE ZARKADES

and

FRANK R. LARSON

DECEMBER 1967

ARMY MATERIALS AND MECHANICS RESEARCH CENTER

WATERTOWN, MASSACHUSETTS 02172

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ABSTRACT

An experimental program was carried out to determine the relationship between texture and the sheet tensile properties. This investigation consisted of extensive testing of eight commercially pure titanium sheets. In each case, chemical analysis, microstructure, X-ray basal pole figure, and tensile properties were determined. The tensile properties were determined at 10-degree increments from the rolling to the transverse direction. In addition to determining the conventional yield strength, tensile strength, and elongation parameters, strain gages were used to obtain Young's modulus and Poisson's ratio in both the elastic and plastic zones.

The sheets investigated had very similar textures, and it was shown that definite anisotropic characteristics were present. The interrelationship between anisotropy and texture is discussed in terms of single-crystal properties.

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INTRODUCTION

It has been known for a long time that materials are anisotropic. In fact, this anisotropy is manifested in most material properties. One of the better known instances is that which arises from microstructures which are multiphase. The ar sotropic characteristics in this case are directly related to the type, amount, shape, and distribution of these phases. The classical example is perhaps the difference in the longitudinal and transverse ductilities in steels. The more complicated type of anisotropy that is of concern here is related to the arrangement of atoms or crystals and is commonly called crystallographic anisotropy.

When an engineer is required to select a material for a certain application, he undoubtedly will first review the various inherent properties of many materials. In his search of the literature for the physical and mechanical properties, he will find that data such as tensile strength, yield strength, Poisson's ratio, percent elongation, etc., are usually given without any mention of location or orientation of the test specimens or if they were taken from material in sheet, rod, or ingot forms.[1,2] For a material that is isotropic and exhibits random orientation of its crystal aggregate, this procedure of reporting results would be satisfactory. However, for a textured or anisotropic material, results presented in this manner are misleading and incomplete. It is this lack of information which prevents the advancement of the use of textured material.

Previous investigators have found that significant variations of elastic and plastic properties exist in many constructional materials.[3,4] These variations have been studied in titanium, a material of increasing commercial importance. To date, however, very little information on the variation of mechanical and physical properties of titanium has been published. In this investigation, extensive testing of unalloyed textured titanium sheets was accomplished. Results clearly indicate that certain preferred orientations will exhibit variations of physical and mechanical properties.

TEST PROCEDURE

Chemical Analysis

Commercially pure titanium RC-55, Ti-100A, and Ti-75A, in sheet form, were tested. These sheets represent both moderately old and fairly recent production. They also cover a range of thicknesses from 0.030 to 0.129 inch. Chemical analysis for the level of impurities and interstitials commonly found in these materials is given in Table I.

Microstructure

The microstructures were determined and are shown in Figures 1A and 1B at 1000X magnification. All structures are indicative of a mill-annealed condition.

Table I. CHEMICAL ANALYSIS COMPOSITION (weight percent)

Material	Thickness (inches)	Heat No.	C	Fe	N	O	H
RC-55	0.125	5-5032BM2	0.031	0.11	0.011	0.136	0.0058
	0.129	53284-BM4	0.060	0.19	0.014	0.143	0.0099
	0.052	53230-2	0.078	0.31	0.019	0.122	0.0098
Ti-75A	0.063	L550	0.025	0.15	0.041	0.223	0.0096
	0.107	M290	0.050	0.12	0.022	0.177	0.0249
Ti-100A	0.030	L657	0.026	0.13	0.033	0.237	0.0370
	0.030	L658	0.032	0.13	0.033	0.266	0.0359
	0.065	L730	0.030	0.10	0.044	0.245	0.0192

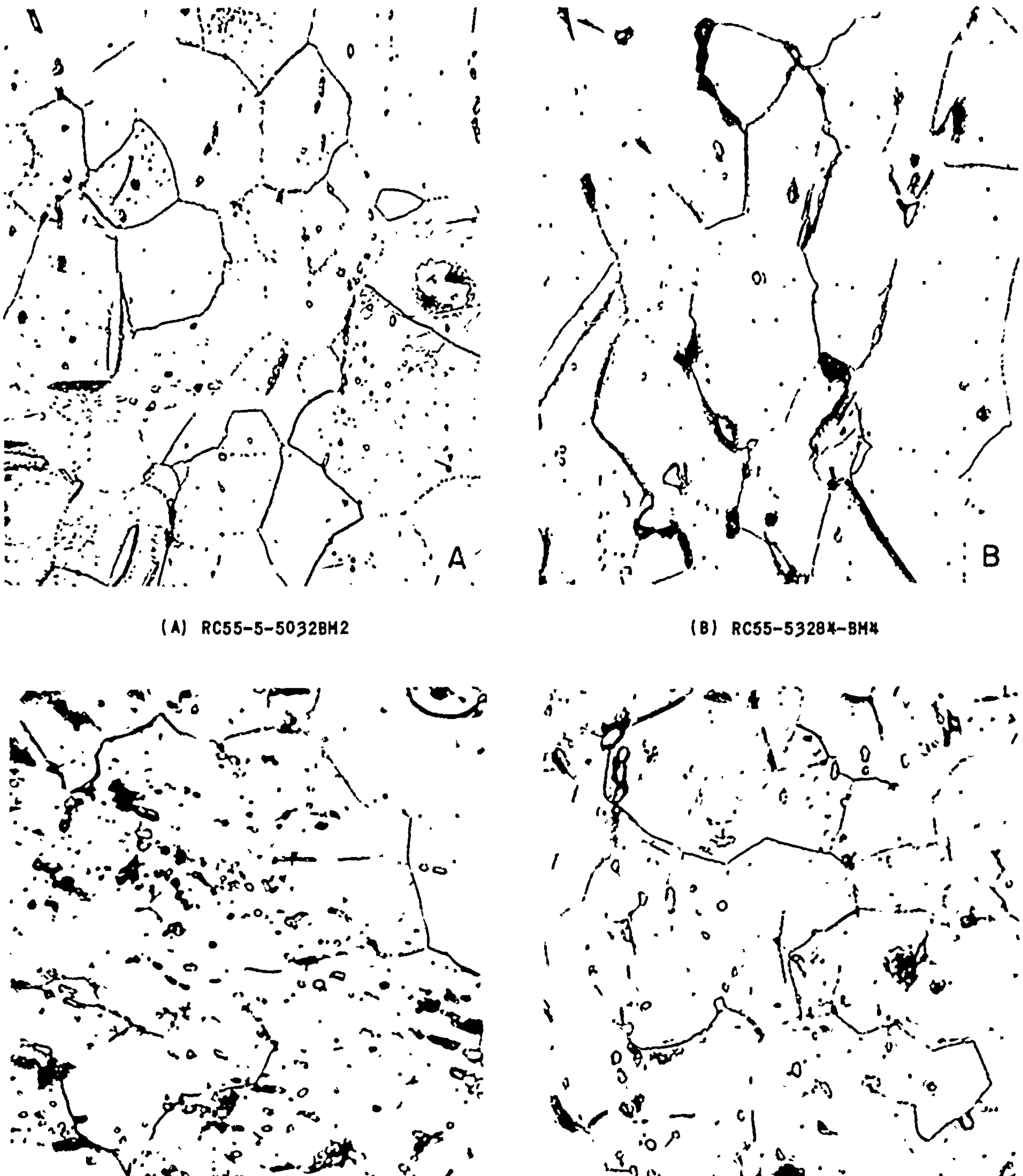
Textures

X-ray diffraction determination of the preferred orientation was carried out using the reflection method described by S. L. Lopata and E. B. Kula[5] and the results are shown in Figure 2. Because of the time and expense, only the pole figures for the basal plane were determined. Furthermore, since most of the properties for hexagonal metals are symmetrical around the basal pole, it was felt that basal pole figures would suffice. The results shown in the figures confirm the general pattern reported by previous investigators.[6] Titanium textures are essentially ones which have a high intensity of their basal poles in the sheet normal-transverse direction plane and which are tilted various angles toward the transverse direction depending upon composition and prior processing history. Comparing the textures with the microstructures, it can be seen that the larger grain size sheets (75A-M290 and RC-55-53230-2) have a more random texture and with a greater intensity of the (0002) poles toward the transverse direction. This texture probably comes from a beta-type preferred orientation and is a result of very little working in the alpha field. Of course, the finer grain sizes (see 75A-L550) showed the strongest texture with the basal pole being closest to the sheet normal. This type of texture has been shown for alpha or cold-worked titanium.[6]

Mechanical Testing

Specimens were machined from the sheets at various angles (α) to the rolling direction, as illustrated in Figure 3. Longitudinal specimens would, therefore, be ones marked 0 degrees or 180 degrees while a transverse specimen would coincide with 90 degrees. Figure 4 shows the geometry of the test specimen utilized throughout this investigation.

Rosette 90-degree, two-element strain gages were bonded to the specimens to measure the strain in the longitudinal (ε_l) and transverse (ε_w) directions. All specimens were tested on a 120,000-pound hydraulic testing machine at a strain rate of 0.005 inch per inch per minute. A schematic of the test setup is illustrated in Figure 5.



(A) RC55-5-5032BH2

(B) RC55-53284-BH4

(C) RC55-53230-2

(D) 75A-L550

Figure IA. MICROSTRUCTURES OF COMMERCIALLY PURE TITANIUM SHEETS AT 1000X

(E) 75A-M290

(F) 100A-L657

(G) 100A-L658

(H) 100A-L730

Figure 1B. MICROSTRUCTURES OF COMMERCIALLY PURE TITANIUM SHEETS AT 1000X

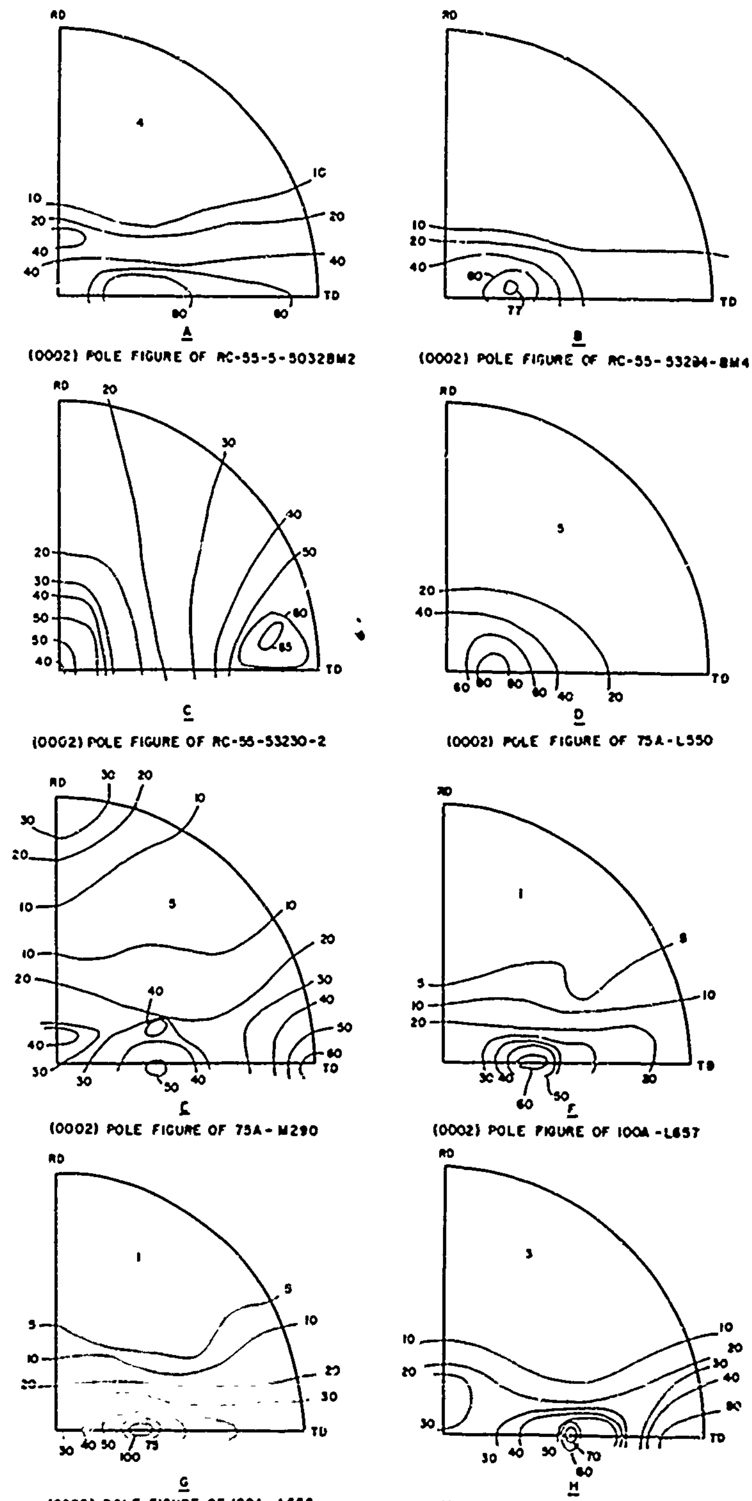


Figure 2. TEXTURES OF COMMERCIALLY PURE TITANIUM SHEETS

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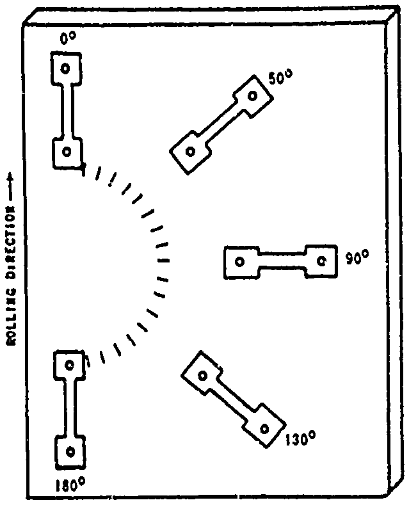

Figure 3. SCHEMATIC OF TENSILE SPECIMEN ORIENTATIONS

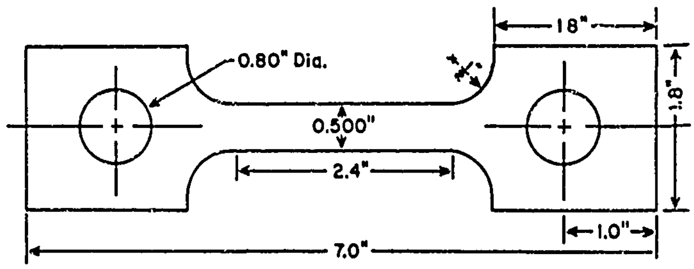

Figure 4. TEST SPECIMEN GEOMETRY

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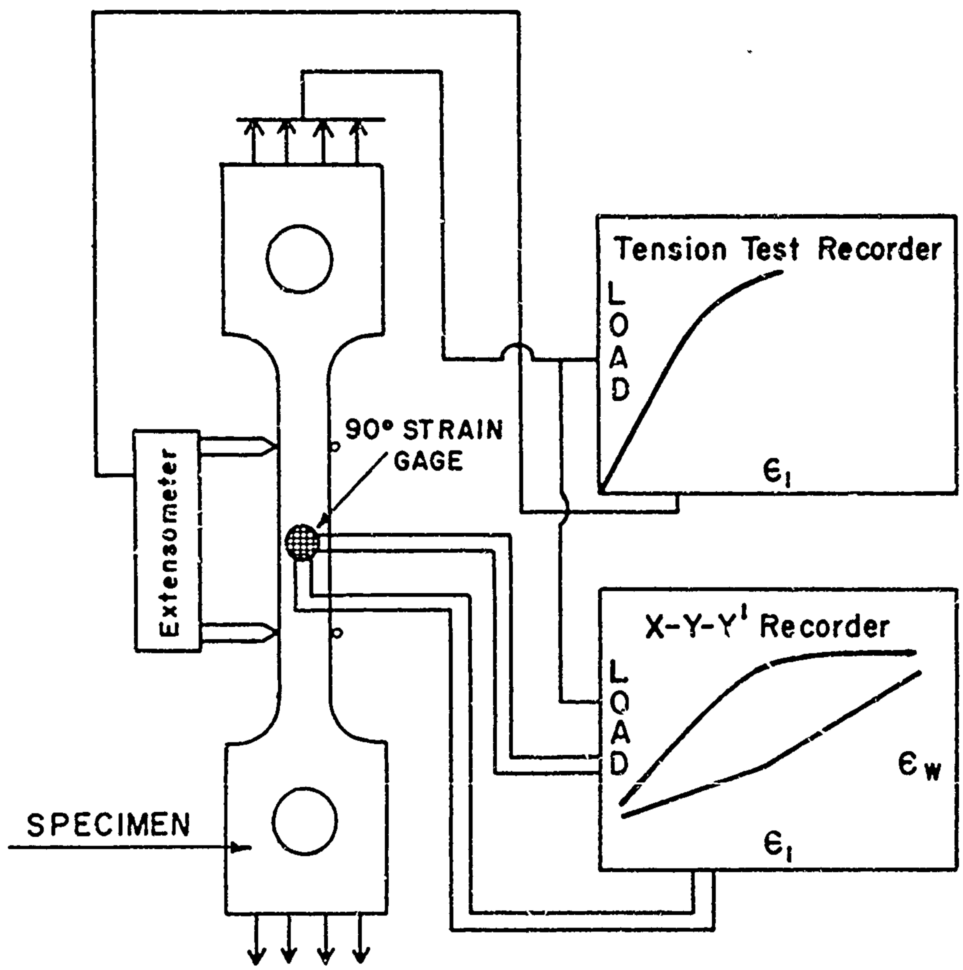

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Figure 5. SCHEMATIC OF TESTING APPARATUS

More testing details and the method of determining various mechanical properties are outlined in a previous report.[7] The tensile test results are shown in Table II.

Table II. MECHANICAL PROPERTIES OF SEVERAL UNALLOYED TITANIUM SHEETS AT VARIOUS SPECIMEN ORIENTATIONS

Specimen Orientation α (degrees)	Heat	Thickness (inch)	μ_E	μ_p	$E\times10^6$ Strain Gage (psi)	Y.S. at 0.1% (ksi)	Y.S. at 0.2% (ksi)	Tensile Strength (ksi)	Elon. (%)
RC-55									
10	S-5032BN2	0.125	0.314	0.473	14.0	54.0	56.0	72.2	
20		0.125	0.353	0.626	15.6	52.7	55.4	70.8	
30		0.125	0.375	0.696	15.5	57.1	59.0	69.6	
40		0.125	0.383	0.734	14.8	57.7	59.4	68.5	
50		0.125	0.375	0.777	16.0	57.5	59.1	67.5	
60		0.125	0.364	0.784	16.4	60.9	62.5	69.9	
70		0.125	0.370	0.764	17.1	61.4	62.8	69.6	
80		0.125	0.387	0.830	16.9	63.5	64.9	72.0	
90		0.125	0.386	0.804	16.8	62.8	64.9	72.8	
100		0.125	0.379	0.855	16.8	62.0	63.5	71.4	
110		0.125	0.373	0.822	16.2	62.3	63.7	70.5	
120		0.125	0.364	0.801	15.9	60.7	62.0	68.8	
130		0.125	0.377	0.785	15.9	59.4	60.9	68.6	
140		0.125	0.357	0.641	16.2	58.2	59.8	68.8	
150		0.125	0.367	0.696	14.9	57.4	59.2	70.0	
160		0.125	0.366	0.658	15.5	55.7	57.9	71.0	
170		0.125	0.364	0.596	15.2	54.4	57.4	73.1	
0	53284-BN4	0.127	0.400	0.764	15.0	62.9	64.7	80.6	31.0
10		0.128	0.394	0.723	15.4	61.9	63.8	78.9	30.5
20		0.127	0.377	0.723	15.5	63.2	63.2	80.0	30.0
30		0.129	0.379	0.751	15.4	62.0	63.7	77.0	31.0
40		0.128	0.388	0.793	15.5	63.2	64.8	74.3	37.0
50		0.129	0.382	0.811	15.6	63.7	65.2	73.9	31.5
60		0.129	0.400	0.839	15.6	65.9	67.3	76.5	31.0
70		0.129	0.393	0.838	15.8	65.8	67.5	75.4	32.0
80		0.131	0.387	0.821	16.0	67.5	69.4	77.1	32.5
90		0.129	0.398	0.824	16.1	67.0	68.9	80.4	27.0
0	53230-2	0.050	0.333	0.483	16.1	59.3	61.2	82.4	31.0
10		0.051	0.343	0.510	16.3	61.0	62.7	83.3	28.0
20		0.052	0.389	0.698	16.0	68.7	70.8	85.6	30.0
40		0.053	0.378	0.815	15.8	74.2	75.8	83.7	29.5
45		0.052	0.387	0.750	16.1	73.4	74.3	81.5	25.0
50		0.052	0.390	0.773	16.4	76.3	77.0	83.4	28.0
70		0.052	0.400	0.765	16.9	78.0	79.5	85.7	26.0
80		0.052	0.387	0.757	16.6	76.8	79.0	85.9	28.0
90		0.051	0.385	0.719	16.9	75.7	76.9	83.7	23.0
Ti-75A									
10	L550	0.063	0.377	0.686	16.1	69.4	72.6	89.4	
20		0.063	0.386	0.707	15.5	69.5	73.0	87.6	
30		0.063	0.382	0.744	15.4	71.1	74.0	87.9	
40		0.063	0.396	0.794	15.6	68.4	70.9	82.8	
50		0.063	0.404	0.831	16.3	70.5	73.3	84.1	
60		0.063	0.392	0.838	16.4	71.1	72.5	84.4	
70		0.063	0.407	0.859	16.5	70.8	73.0	83.8	
80		0.063	0.414	0.873	17.2	71.1	73.2	85.1	
90		0.063	0.404	0.855	17.0	71.4	73.3	84.4	
100		0.063	0.407	0.857	16.7	70.1	72.3	82.9	
110		0.063	0.404	0.859	16.4	71.8	73.7	83.9	
120		0.063	0.404	0.848	16.4	70.4	72.5	82.3	
130		0.063	0.393	0.812	16.0	68.5	70.4	81.9	
140		0.063	0.396	0.787	15.4	68.8	71.0	83.0	
150		0.063	0.386	0.759	16.1	69.5	71.7	84.7	
160		0.063	0.386	0.706	15.4	69.6	72.0	87.3	
170		0.063	0.386	0.683	15.5	68.0	70.9	38.3	

Table II. MECHANICAL PROPERTIES OF SEVERAL UNALLOYED TITANIUM SHEETS AT VARIOUS SPECIMEN ORIENTATIONS (continued)

Specimen Orientation α (degrees)	Heat	Thick-ness (inch)	μ_E	μ_p	$E \times 10^6$ Strain Gage (psi)	Y.S. at 0.1% (ksi)	Y.S. at 0.2% (ksi)	Tensile Strength (ksi)	Elon. (%)
				Ti-75A (continued)					
0	H290	0.107	0.322	0.438	15.8	65.2	67.8	87.2	
10		0.107	0.331	0.466	14.4	66.2	69.3	87.6	
20		0.107	0.333	0.488	15.8	66.6	69.3	87.3	
30		0.107	0.345	0.551	15.4	68.0	70.7	86.1	
40		0.107	0.357	0.600	14.9	68.0	71.6	84.8	
50		0.107	0.364	0.652	16.5	67.6	70.7	84.0	
60		0.107	0.346	0.673	15.8	71.1	13.8	85.9	
70		0.107	0.380	0.720	17.0	74.1	76.7	88.8	
80		0.107	0.369	0.697	17.4	73.4	76.5	90.2	
100		0.107	0.365	0.696	17.3	77.5	80.0	91.4	
110		0.107	0.359	0.712	16.2	73.1	76.4	88.2	
120		0.107	0.358	0.699	17.1	72.7	75.6	87.0	
130		0.107	0.351	0.671	15.2	71.0	73.6	86.0	
140		0.107	0.350	0.620	15.4	69.8	72.2	85.7	
150		0.107	0.350	0.554	14.4	67.8	70.8	86.1	
160		0.107	0.333	0.462	14.5	67.8	70.2	87.0	
170		0.107	0.339	0.479	15.3	66.2	68.9	87.8	
				Ti-100A					
0	L657	0.029	0.352	0.552	15.4	72.8	76.6	96.6	22.0
10		0.030	0.356	0.552	15.7	70.0	74.0	94.3	28.0
20		0.030	0.364	0.587	15.2	70.3	74.3	93.3	27.5
30		0.030	0.400	0.666	15.4	68.9	71.7	88.0	29.5
40		0.030	0.391	0.725	15.2	68.3	73.0	88.7	28.5
50		0.030	0.393	*	15.2	68.7	73.3	89.0	27.5
60		0.030	0.393	0.522	15.5	72.0	76.7	90.0	28.0
80		0.030	0.400	0.713	16.0	74.0	78.0	92.0	27.0
90		0.029	0.358	0.631	15.7	73.8	77.6	93.1	23.0
0	L658	0.030	0.349	0.547	15.5	69.7	74.0	96.0	20.5
10		0.030	0.357	0.523	15.7	73.3	76.7	96.7	23.0
20		0.029	0.353	0.516	15.7	75.9	79.7	97.9	22.0
30		0.030	0.362	0.614	15.9	75.7	79.3	95.3	31.0
40		0.030	0.381	0.683	15.9	78.7	81.3	94.7	26.5
50		0.030	0.375	0.677	17.2	78.1	81.5	94.7	26.0
60		0.030	0.386	0.719	17.2	82.8	86.4	98.7	28.5
70		0.030	0.381	0.714	17.5	77.7	81.7	95.3	25.5
80		0.031	0.411	0.692	17.0	79.0	82.6	95.8	26.5
90		0.031	0.390	0.692	16.5	79.6	84.2	100.7	23.0
0	L730	0.065	0.330	0.451	14.5	71.0	74.1	94.4	23.0
10		0.065	0.332	0.481	14.7	75.0	77.2	97.8	21.0
20		0.065	0.349	0.545	15.0	76.9	80.2	99.4	24.5
30		0.065	0.340	0.545	15.3	72.1	75.2	94.5	25.0
40		0.065	0.360	*	15.7	78.2	81.3	95.1	26.5
50		0.065	0.351	0.663	16.5	76.7	80.4	95.1	31.0
60		0.065	0.370	0.700	16.5	76.5	79.6	94.9	28.0
70		0.065	0.374	0.703	17.3	84.6	87.4	100.3	28.0
80		0.065	0.374	*	17.6	83.3	86.1	140.0	28.0
90		0.065	0.365	0.625	17.7	84.6	87.4	105.6	25.0

**Strain gage failed.*

Because of the symmetry of sheet tensile properties around the rolling direction, results plotted for material where specimens were obtained at orientations 0 through 180 degrees are averages of identical orientations (i.e., 10 and 170 degrees are both 10 degrees from rolling direction). Data plotted in this manner are parts A, D, and E of all mechanical test results. Because of lack of material, the longitudinal tests were omitted for some sheets.

DISCUSSION OF RESULTS

Young's Modulus

It is known that for hexagonal single crystals that Young's modulus is sensitive to the angle that the applied stress makes with the basal pole and is symmetrical about this pole.[8] Determination of Young's modulus on single crystals of titanium[9] have shown that Young's modulus is lowest (14.5×10^6) when the stress axis lies in the basal plane and highest ($2?.0 \times 10^6$) when the stress axis coincides with the basal pole.[10] It should, therefore, be expected that this single crystal orientation effect would be observed in strongly textured polycrystalline material.

It can be seen from the above and the textures prevalent in these titanium sheets that the lowest Young's modulus should appear in the rolling direction since the greatest number of grains would have the stress axis closest to the basal plane. If the texture were random or if the basal planes are parallel to the sheet surface, we would expect no variation of Young's modulus with specimen orientations. However, if a strong texture is present, the variation of Young's modulus depends upon the tilt of the basal poles toward the transverse direction. The sheet having the greatest intensity of basal poles in the transverse direction will have the largest variation of Young's modulus with the largest value occurring in the transverse direction. An excellent example of this is illustrated in Figure 6H.

Poisson's Ratio

Another elastic property, which is less frequently used, is Poisson's ratio. Just as the elastic modulus in single crystals is sensitive to orientation, so is Poisson's ratio. It has been shown[7] that among titanium and its alloys Poisson's ratio can vary from about 0.20 to 0.44. Later studies of titanium single-crystal data indicate that this range may be even greater.[3] Thus, it is expected that those sheets exhibiting a strongly developed texture of certain orientations will have a small but significant variation on Poisson's ratio. Examination of the curves in Figure 7 reveals that this is essentially true. Analysis of the textures in the various sheets tested shows that those sheets having the strongest texture and with the greatest concentration of basal pole tilting toward the transverse direction have the lowest Poisson's ratio in the rolling direction.

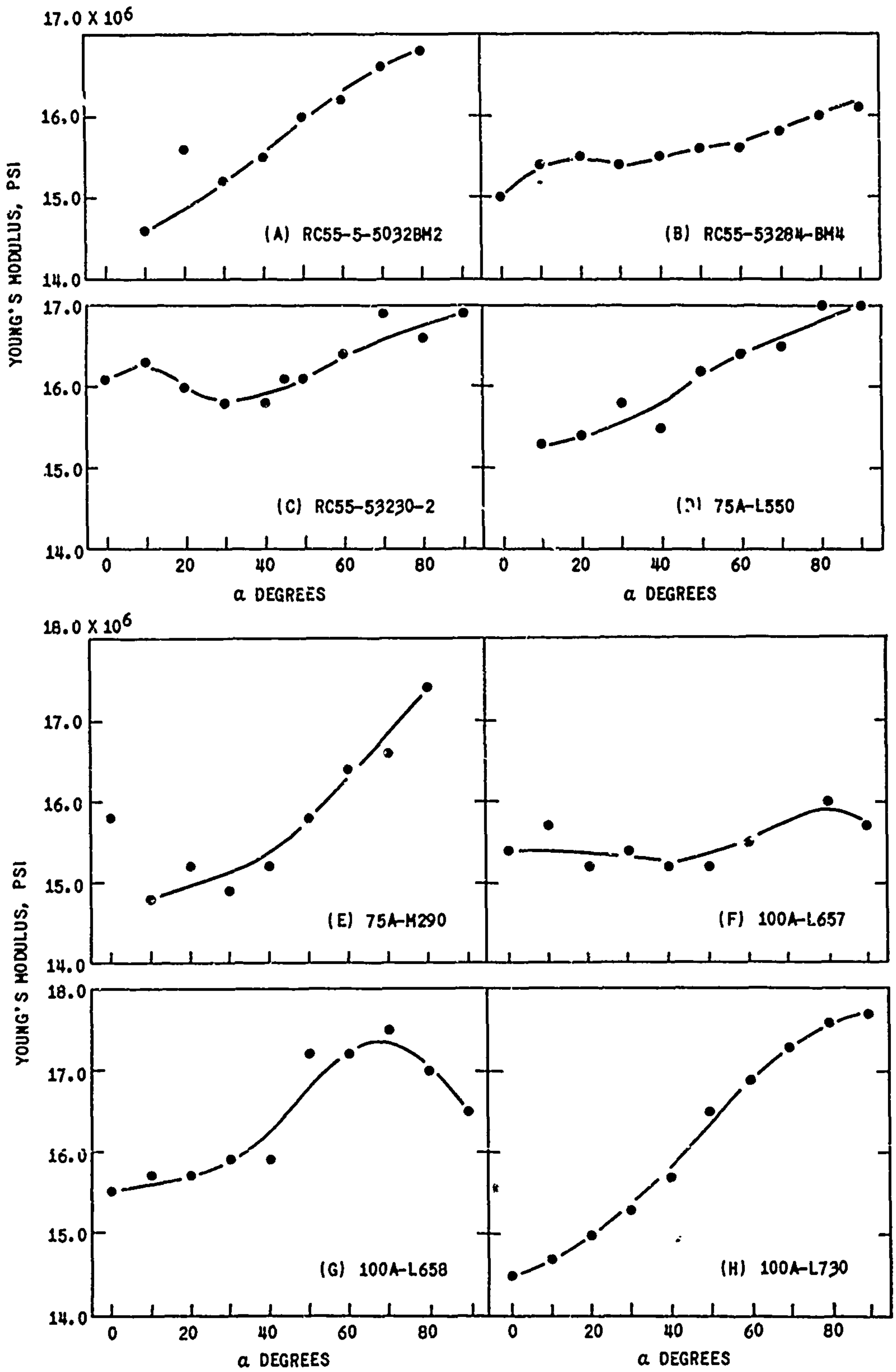

Figure 6. VARIATION OF YOUNG'S MODULUS (E) WITH SPECIMEN ORIENTATION

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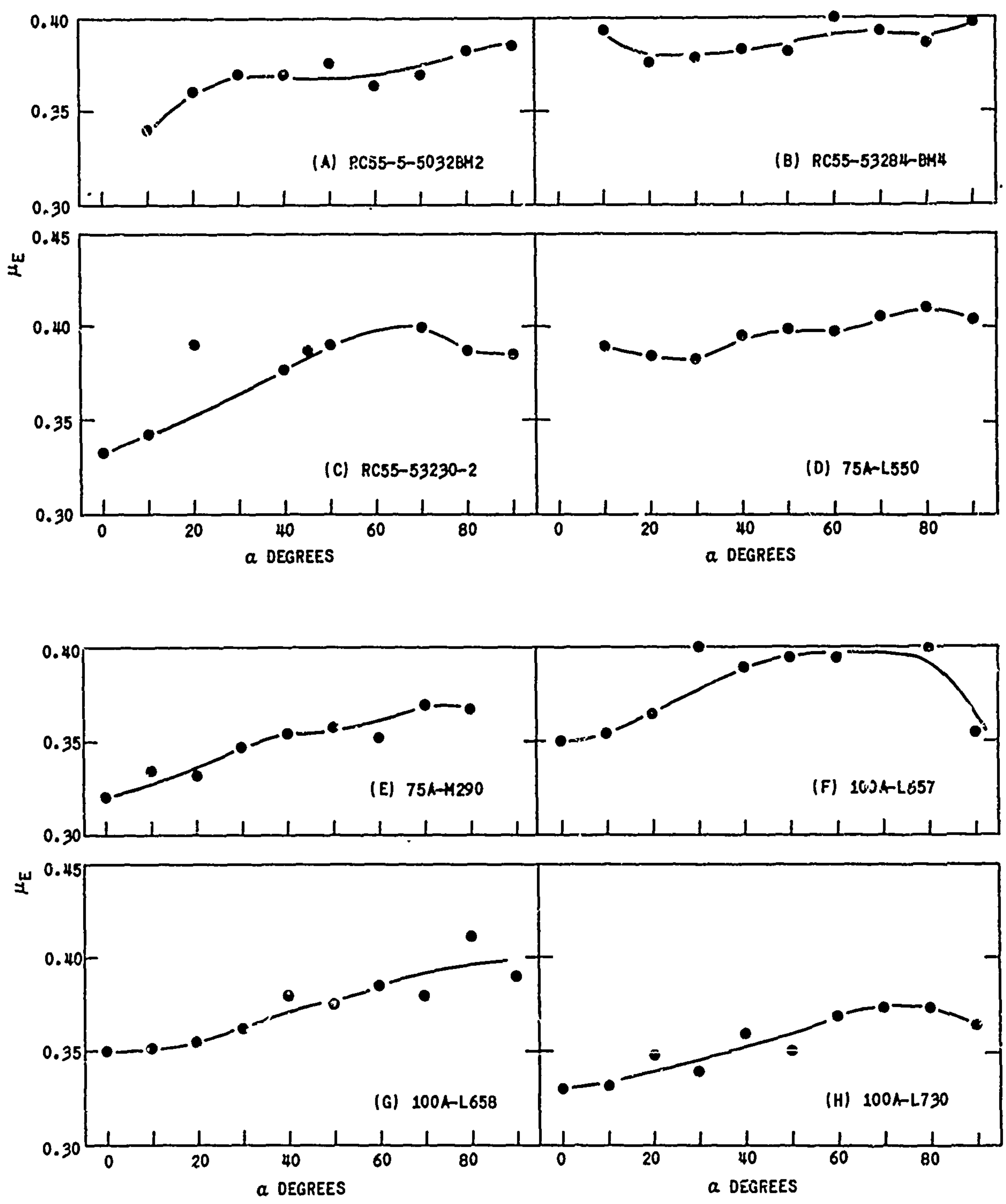

Figure 7. VARIATION OF POISSON'S RATIO IN THE ELASTIC ZONE (μ_E) WITH SPECIMEN ORIENTATION
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Yield Strength

Research work on single crystals also clearly demonstrated that the yield strength is a function of orientation;[8] however, it is much more complicated than the previous properties discussed. In any event, one would expect that, as with the other properties, the yield strength would vary with orientation. This can be seen by examination of Figure 8. Generally, it was found that yield strength was lowest in the rolling direction and increased gradually as the specimens approached the transverse direction. Those sheets with the strongest texture and with the basal poles nearest the transverse direction had the largest variation in yield strength.

This is illustrated by sheets RC-55-53230-2 and 100A-L730 which had variations of approximately 20,000 psi and 15,000 psi, respectively see Figures 8C and 8H.

Tensile Strength

The tensile strength depends upon two factors; first, the yield strength and then the rate of work hardening. Both factors are orientation-dependent in a very complicated way so that it will be very difficult to make specific predictions about the tensile strength. Examination of the experimental results shown in Figure 9 indicates the complicated trends. In general, a minimum is found at 40 to 50 degrees from the rolling direction with a high value in the rolling direction and a higher one in the transverse direction.

Plastic Strain Ratio

Of all material properties, the ratio of plastic strains ($\varepsilon_W/\varepsilon_l$) is probably more sensitive to texture than the others. This is clearly evident from examination of Figure 10. Notice the large variation in plastic Poisson's ratio with the lowest values being in the rolling direction and the highest in the transverse direction. Again the sheets with the strongest texture and greater tilt of the basal plane poles toward the transverse direction produce the greatest variation.

Exemplified by results observed in Poisson's ratio in the plastic zone is the necessity for proper reporting of physical and mechanical data of textured materials. As can be seen in Figures 10A and C, large variations do exist in Poisson's ratio with varying specimen orientation, approximately 0.50 to 0.80. Converting to the more commonly used anisotropy parameter R, one finds the variation to be 1 to 4. If the interest is in the deep drawing characteristics of these particular materials, results from only the longitudinal tests would be misleading.

Elongation

The percent elongation was not determined on all sheets and the available information is illustrated in Figure 11. There is insufficient data to clearly define a trend, but there does appear to be a mild tendency for the values to peak at angles around 45 degrees from the rolling direction.

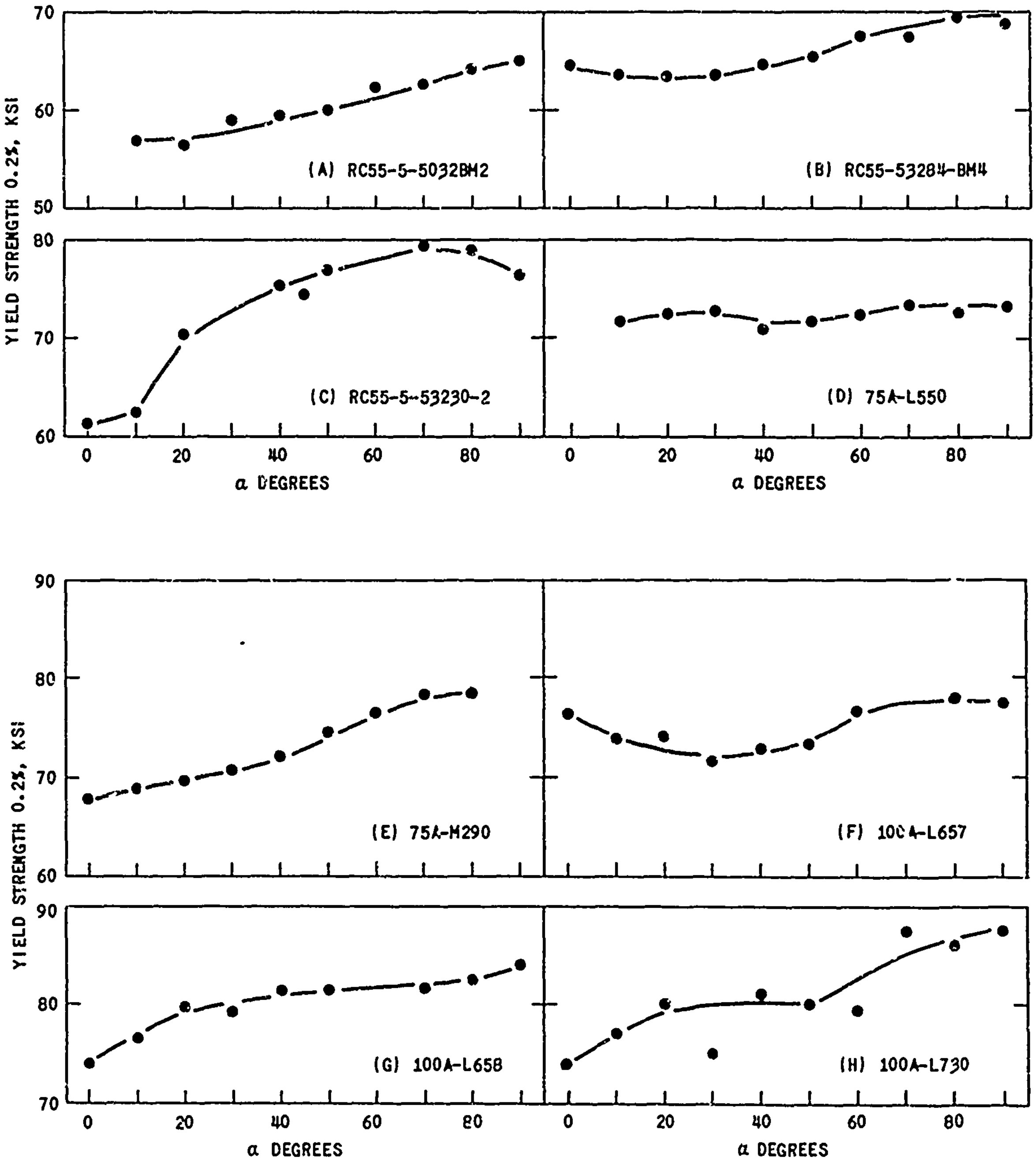

Figure 8. VARIATION OF YIELD STRENGTH WITH SPECIMEN ORIENTATION

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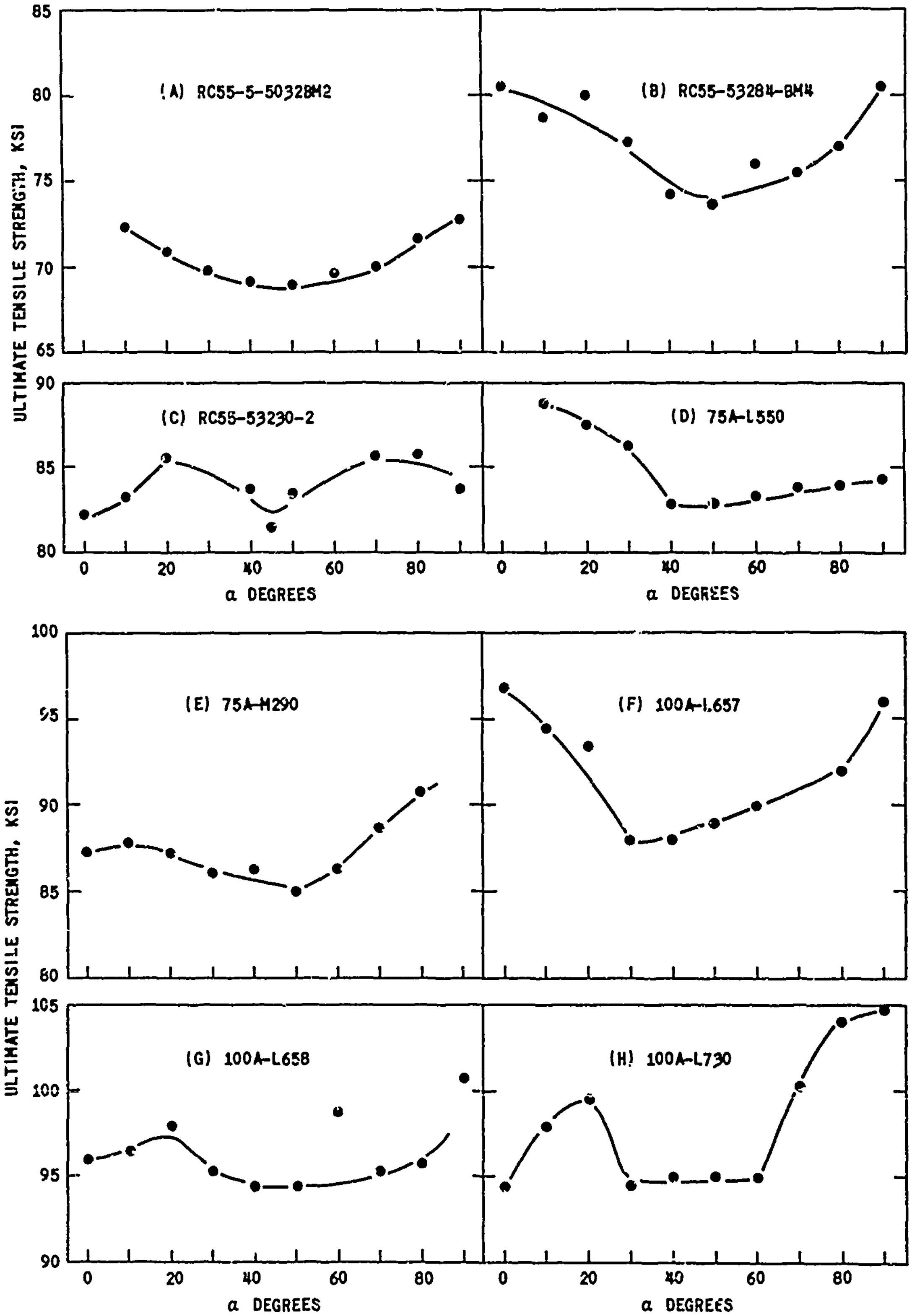

Figure 9. VARIATION OF TENSILE STRENGTH WITH SPECIMEN ORIENTATION

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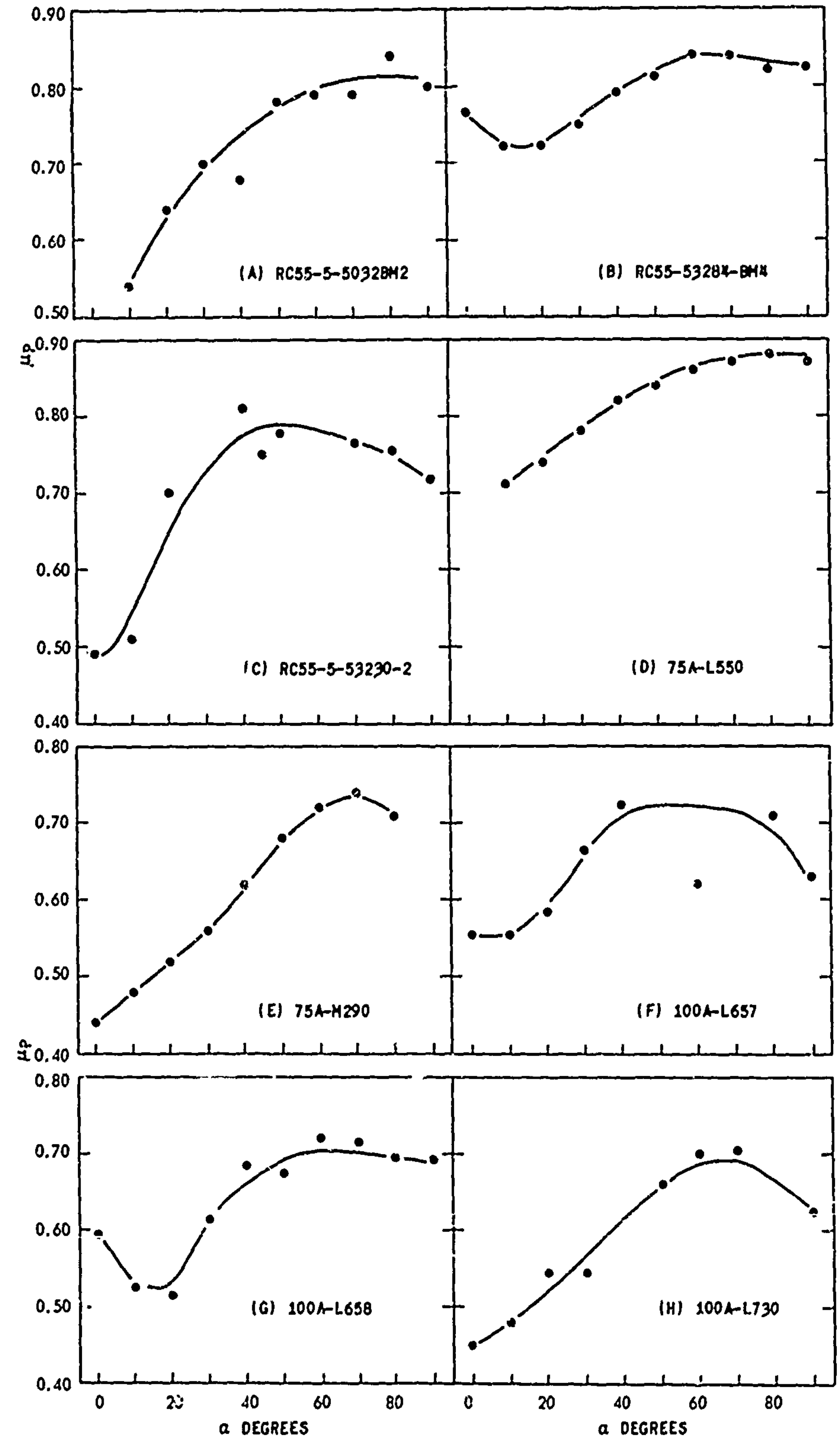

Figure 10. VARIATION OF POISSON'S RATIO IN THE PLASTIC ZONE (μ_p) WITH SPECIMEN ORIENTATION

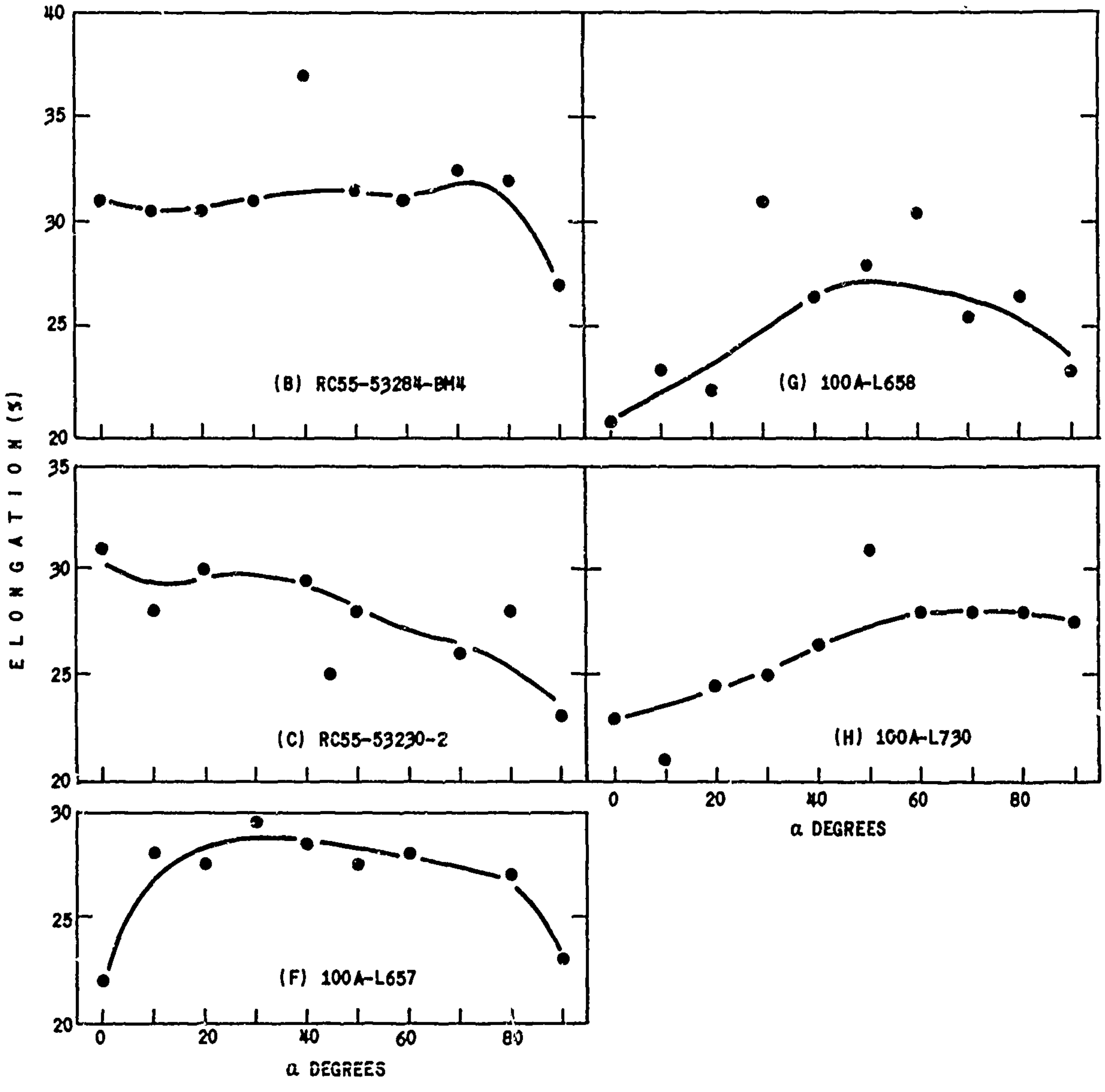

Figure 11. VARIATIONS OF PERCENT ELONGATION WITH SPECIMEN ORIENTATION

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SUMMARY

It is clearly established from the sheets tested that unalloyed titanium sheets are and can be anisotropic with respect to their uniaxial tensile properties. This can be observed in both the elastic and plastic characteristics. It is also shown that there is a definite relationship between textures and mechanical properties.

Hopefully, data presented in this report will be utilized in future studies of textured materials, their applications, or analyses. It is realized that a great deal of further effort needs to be expended in defining heat treatment and deformation parameters necessary to obtain specific desirable textures which once controlled may offer a tremendous potential for improved mechanical properties, especially in hexagonal close-packed metals.

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13. ABSTRACT An experimental program was carried out to determine the relationship between texture and the sheet tensile properties. This investigation consisted of extensive testing of eight commercially pure titanium sheets. In each case, chemical analysis, microstructure, X-ray basal pole figure, and tensile properties were determined. The tensile properties were determined at 10-degree increments from the rolling to the transverse direction. In addition to determining the conventional yield strength, tensile strength, and elongation parameters, strain gages were used to obtain Young's modulus and Poisson's ratio in both the elastic and plastic zones.

The sheets investigated had very similar textures, and it was shown that definite anisotropic characteristics were present. The interrelationship between anisotropy and texture is discussed in terms of single-crystal properties. (Authors)

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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